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# **A Fusion Chamber for the 2002 Robust Point Design**

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## **A Fusion Chamber for the 2002 Robust Point Design**

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### **ABSTRACT**

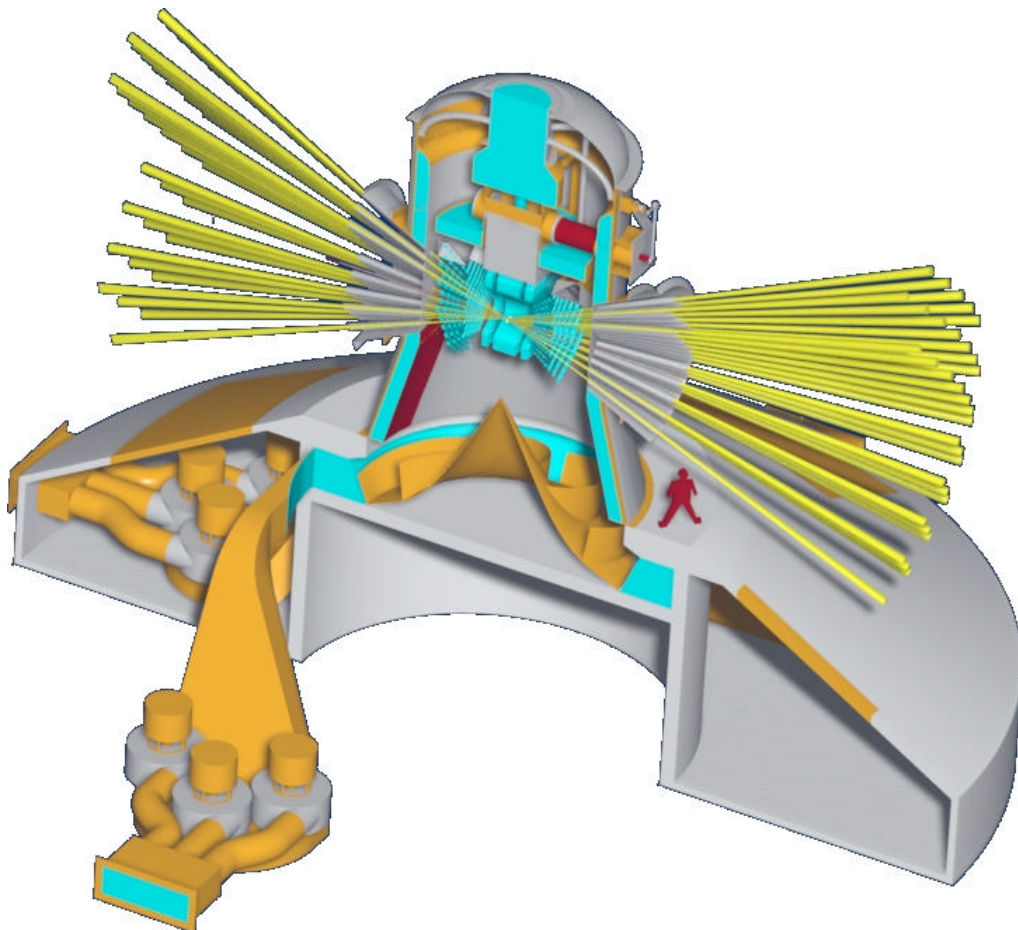
A top-level overview of the mechanical design for the 2002 Robust Point Design (RPD-2002) fusion chamber is introduced. It is based on the HYLIFE-II design and includes modifications to the liquid pocket configuration and first structural wall (FSW), facilitates periodic maintenance or replacement of internal components, and is compliant with all other RPD-2002 parameters. This work has been carried out by constructing a parametric computer model capable of being updated as future changes become necessary.

### **INTRODUCTION**

RPD-2002 is an attempt to present a self-consistent picture of a heavy ion inertial fusion energy (HIF) power plant by integrating the latest understanding of target physics, drivers and beam focusing, chamber dynamics, and radiation shielding [1]. A HYLIFE-II style 2,3] thick liquid protected fusion chamber featuring an updated pocket configuration is proposed for RPD-2002. This chamber type can make possible substantially longer chamber component lifetimes compared to what can be achieved with dry and wetted wall concepts, the ultimate goal being for them to survive the lifetime of the plant.

This document summarizes a mechanical design for the fusion chamber that is fully compatible with other plant parameters. The design also adds functionalities not found in HYLIFE-II including a capability for periodic repair or replacement of internal chamber components if radiation damage limits necessitate such action. Other chamber features have been modified to be more robust in light of recent materials failure concerns. Primary among these is the design of the FSW where the arrays of vertical tubes found in the HYLIFE-II design have been replaced by a flexible woven-wire steel mesh to mitigate stresses from neutron induced swelling.

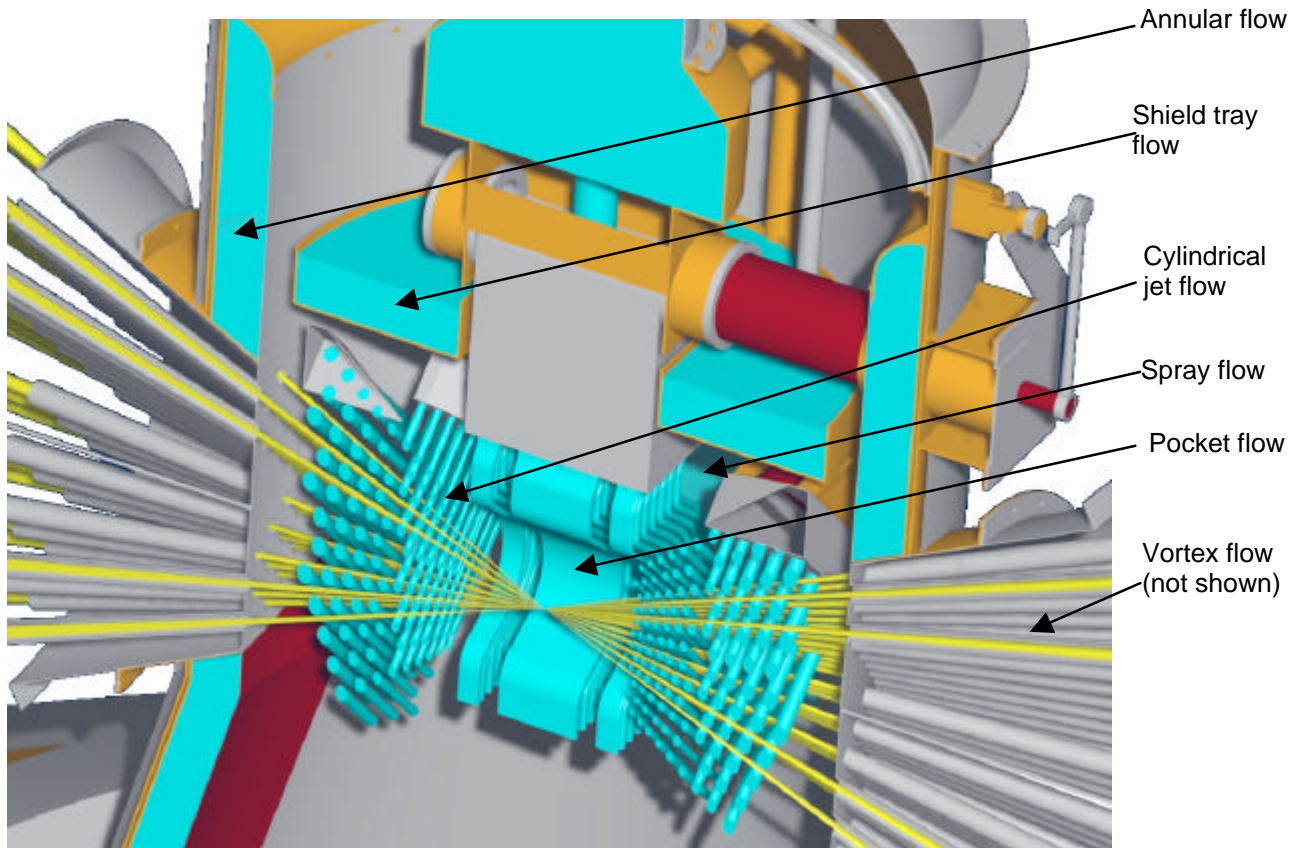
Using conservative parameters, RPD-2002 focuses on demonstrating feasibility rather than setting a design point optimized for the most inexpensive energy production. Consequently, it is not believed that RPD-2002 represents the final design for a first generation HIF power plant. Changes to all plant systems will undoubtedly be proposed as understanding improves and new ideas are developed. The fusion chamber will be no exception. Its mechanical design has been carried out with this in mind. Figure 1 shows the parametric 3-D solid model of the chamber that was created with the design package Pro/Engineer. The benefits of using parametric computer modeling are multifold. Having such a model allows presentations of the chamber geometry that are easier to grasp than 2-D drawings. Also, chamber components can be easily exported to numerical analysis routines for studying their reactions to various chamber phenomena. The greatest advantage, though, is the ability to quickly modify the chamber design without starting from scratch.



**Fig. 1** The RDP-2002 fusion chamber CAD model.

## LIQUID PROTECTION FLOW CONFIGURATION

The molten salts Flibe ( $\text{Li}_2\text{BeF}_4$ ) and Flinabe ( $\text{LiNaBeF}_4$ ) have been identified as candidates for the RPD-2002 fusion chamber thick liquid protection system. This system is composed of several distinct molten salt flows (see Figure 2). All have the general function of shielding solid components from target output x-rays and neutrons, but the specific configuration of each type of flow is dictated by its location in the fusion chamber and the physical processes it is attempting to control.



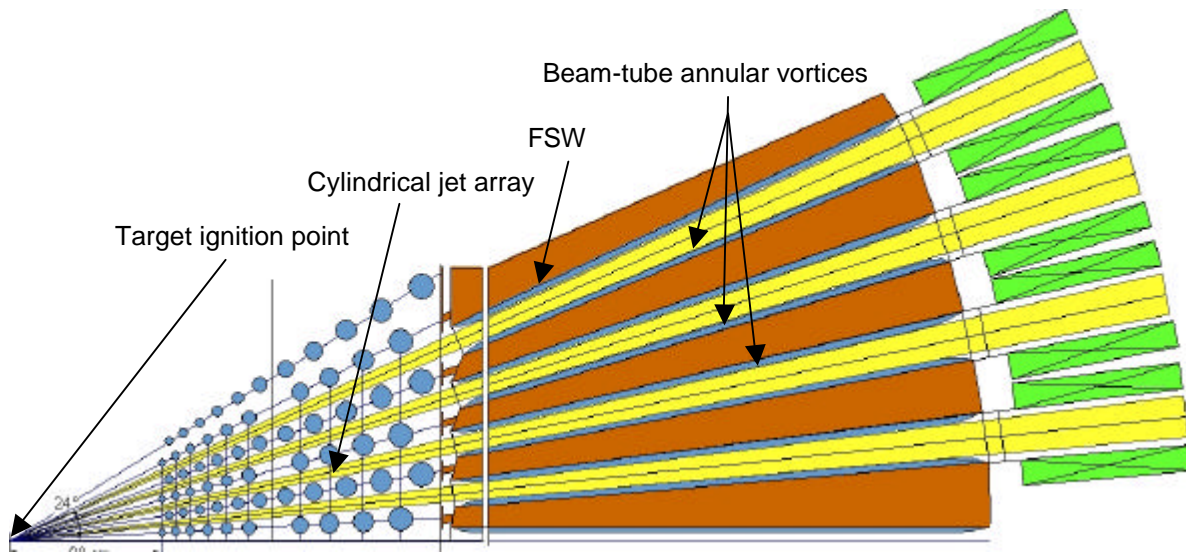
**Fig. 2** Thick liquid protection system molten salt flows.

The flow producing the central pocket is produced from molten salt exiting at 12 m/s from nozzles actuating at the target injection frequency of 6 Hz. When a pocket reaches the proper location, a target is injected along its horizontal axis toward the center of the chamber where it is ignited by ion beams.

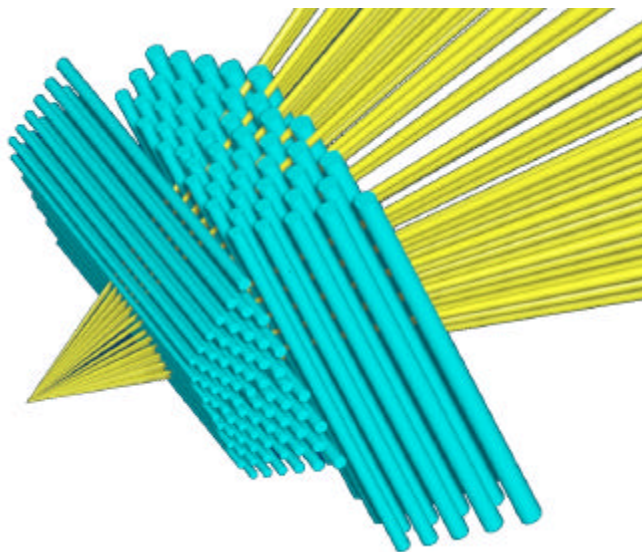
If the pocket were a monolithic flow of full density molten salt, shocks from x-ray ablated target facing surfaces and neutron isochoric heating would eject damaging high

speed droplets toward the FSW and other structures. The pocket flow is therefore composed of arrays of small cylindrical jets that mitigate the formation of these shocks [4]. Large vent channels allow vaporized salt to exit the pocket and new pockets actively sweep droplets and other debris from the target ignition region after each shot.

An array of cylindrical jets shields components located inline with the horizontal axis of the pocket while allowing for ion beam propagation and target injection [5]. Figure 3 shows a schematic layout of this array, and Figure 4 shows its three dimensional representation.

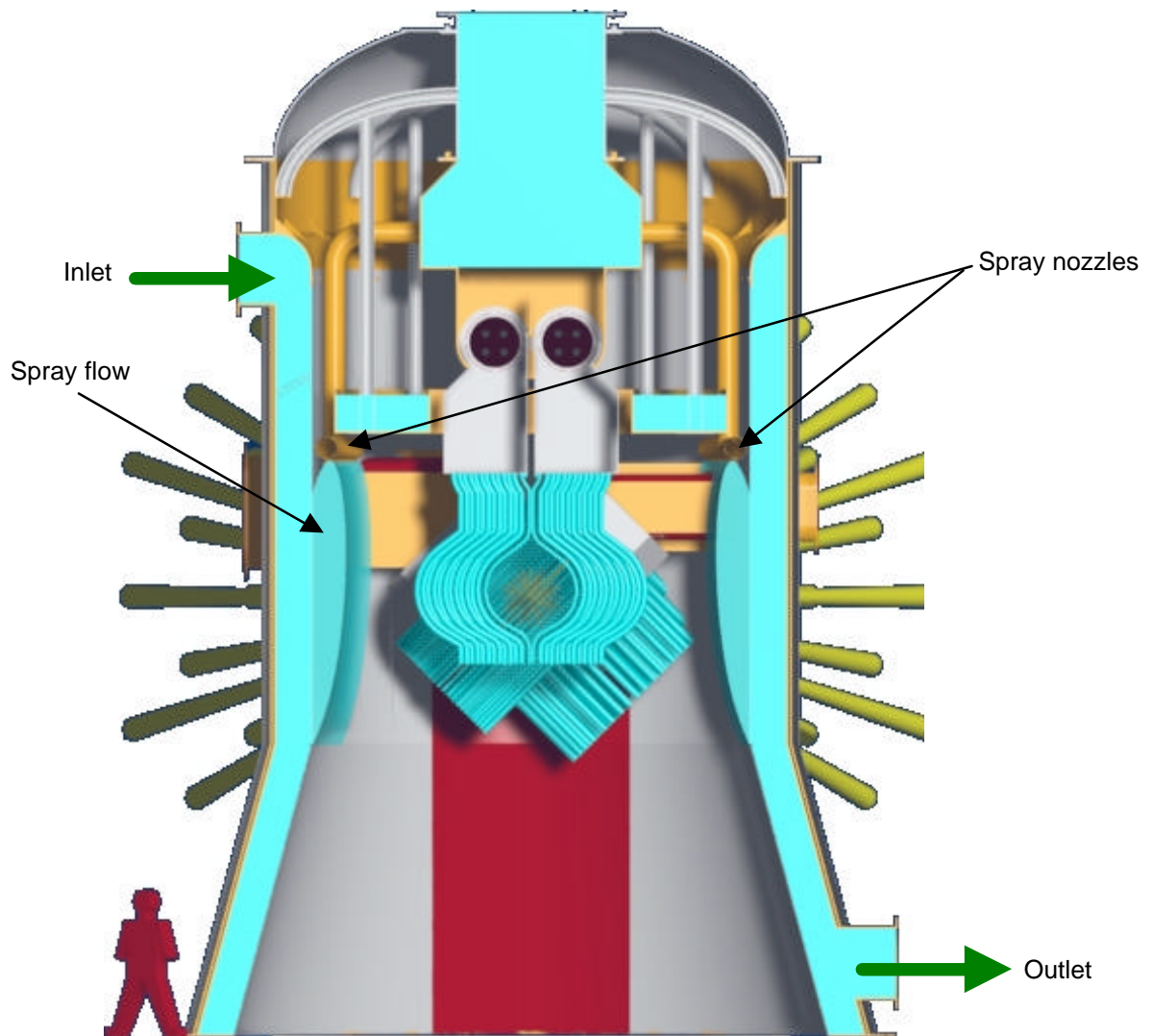


**Fig. 3** A schematic layout of cylindrical jet array.



**Fig. 4** Three dimensional cylindrical jet array.

Because the cylindrical jets form square apertures through which the ion beams pass, beam-tube walls would have a direct line of sight to the target and be exposed to damaging x-rays and increased neutron fluences. The tube walls are lined with annular vortex flows (also shown in Figure 3) to protect these structures. To generate these vortices, molten salt is injected tangent to the tube walls with an axial velocity component. The swirling liquid protects the walls while allowing ion beams to pass without interference [6]. Once the liquid reaches the end of the beam tube at the fusion chamber interface, it is allowed to fan out and is then redirected downward behind the FSW.



**Fig. 5** Annular flow inlet and outlet.

A pool of molten salt 0.5 m deep can also be seen in Figure 2. It resides in the shield tray above the pocket flow to further reduce neutron fluences to structures in the upper regions of the fusion chamber. Fed from supply lines emanating from the incoming pocket flow and draining down the face of the FSW, the liquid in this pool is replaced on a continuous basis.

Behind the FSW a confined annular molten salt flow 0.5 m thick provides additional neutron shielding to the fusion chamber vacuum vessel. This flow is divided into two regions. The first is supplied by the inlet port diagrammed in Figure 5 and feeds toward the outlet port shown. The second region resides behind the red section of FSW shown in Figure 5. It is supplied by molten salt extracted from the beamline vortex flows above. This salt is allowed to join the rest of the inner chamber free surface flows at the bottom of the chamber.

The nozzles on both sides of the chamber shown in Figure 5 produce molten salt sprays outside the pocket flow. The millions of droplet surfaces associated with this flow serve as condensation sites for the vaporized salt resident in the chamber after a fusion target ignition [1].

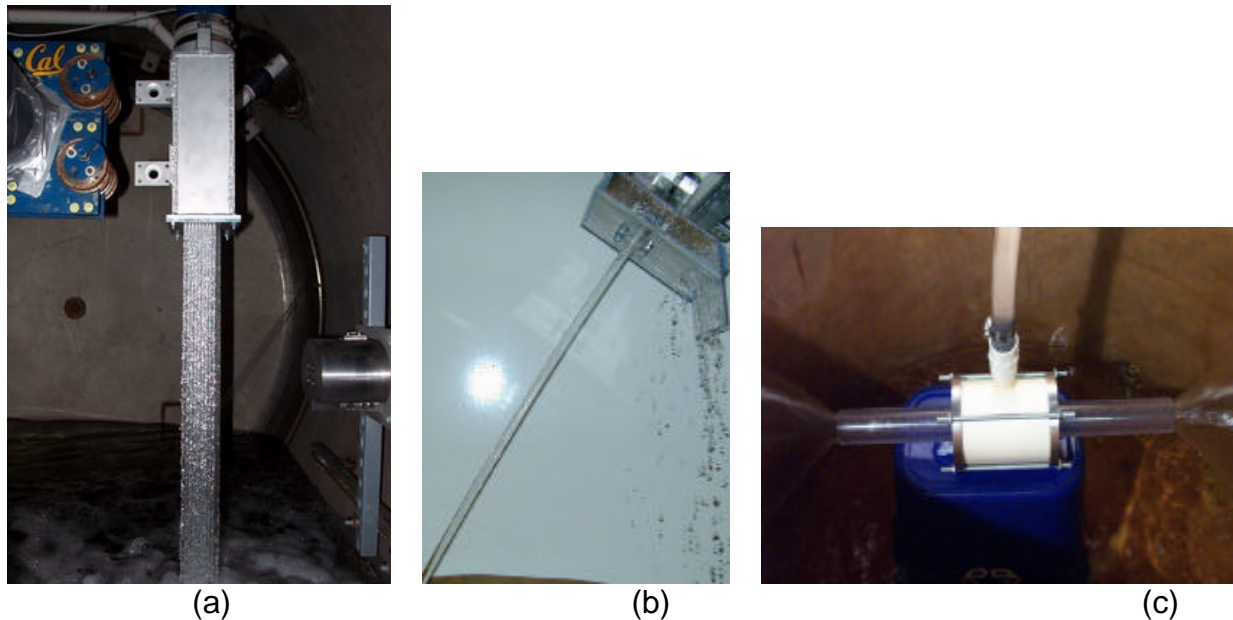
## LIQUID PROTECTION PUMPING SYSTEM

The volumetric flow rates of several of the flow systems described above are dependent upon plant repetition rate (the rate at which fusion targets are ignited). A value of 6 Hz has been assumed in all calculations including the determination of values shown in Table 1 below. The pocket flow and cylindrical jet arrays account for 80% of molten salt entering the RPD-2002 fusion chamber.

**Table 1** Molten salt volumetric flow rates.

Flow System	Q (m <sup>3</sup> /s)
Pocket flow	26.5
Jet arrays	20.3
Vortex flows	5.3
Annular flow	3.5
Shield tray	1.6
Spray flow	2.0
<b>Total</b>	<b>59.2</b>

Each molten salt flow must traverse geometric features resulting in flow energy losses. For the pocket, jet arrays, and vortices the magnitude of these losses can have a significant impact on the pumping power required to drive the thick liquid protection system. Efforts have therefore been made to measure the loss coefficients for these flows in scaled water experiments such as those shown in Figure 6 [7].



**Fig. 6** Scaled experiments for (a) pocket flow, (b) cylindrical jet, (c) and vortex flow.

The loss coefficients (Table 2) were then incorporated into calculations to determine the pumping powers associated with each flow system (Table 3).

**Table 2** Loss coefficients.

Flow System	$K_l$
Pocket flow	~2.0
Jet arrays	~3.0
Vortex flows	~3.0

**Table 3** System pumping powers.

Flow System	P (MW)
Pocket flow	9.6
Jet arrays	11.0
Vortex flows	3.4
Annular flow	2.5
Shield tray	0.1
Spray flow	0.9
<b>Total</b>	<b>27.5</b>

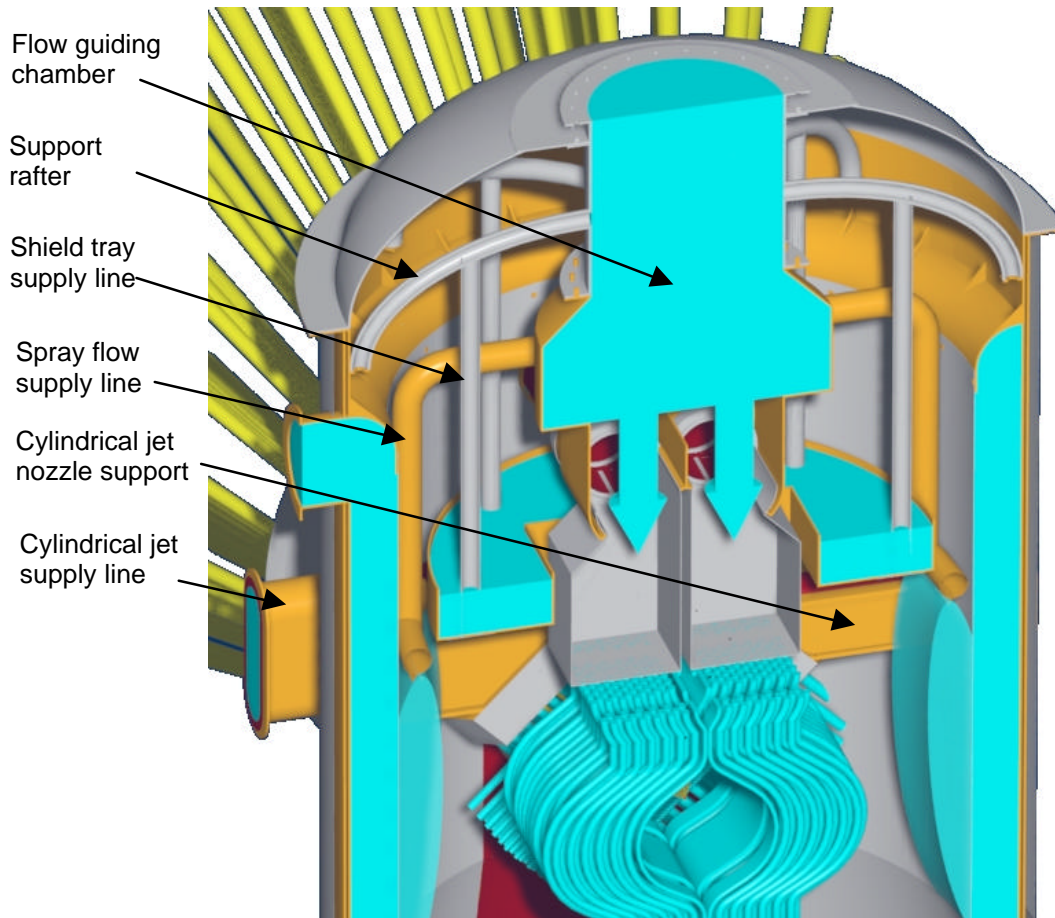
The large turning vanes at the bottom of the fusion chamber redirect the various downward moving free surface flows into a rotating mass of molten salt [3]. This is a critical element of the fusion chamber's head recovery system that feeds a supply of quiescent molten salt to the four diffusers located at the bounding edge of this flow. Inside these diffusers the static pressure of the flow rises before reaching the twelve molten salt pumps that drive the system.

## **INTERNAL CHAMBER STRUCTURES**

To generate the free surface flows detailed above requires several internal chamber structures and mechanisms. Some of these components are static and require no moving parts while others, such as the pocket nozzle drive system, will experience large dynamic forces as they oscillate at the plant repetition rate. Materials damage from energetic neutron irradiation threatens the survival and reliability of these components over the plant lifetime and the mechanical design of the fusion chamber has been carried out with this in mind. But before getting to the details of how the design addresses these issues, an overview of these internal chamber components is in order.

The pocket flow surrounding targets is generated from molten salt flowing from two oscillating nozzles directly above the target ignition point. These nozzles are suspended within the larger flow guiding chamber (seen in Figure 7) which directs molten salt from a port in the chamber top. They are actuated by a pair of drive shafts that protrude through the fusion chamber wall where they are driven from a large electric motor. The nozzles are mounted within the guiding chamber in a sleeve that functions as a hydraulic bearing to balance the reaction forces from the pocket flow. The drive shafts transmit only torsion forces to the system making their support and sealing much simpler than in the HYLIFE-II chamber design [3, Fig. 5].

The spray flow is generated with molten salt from the flow guiding chamber that also supplies the pocket nozzles. The tubes that connect the spray nozzles with the flow guiding chamber also mechanically support the nozzles against gravity and the relatively small reaction forces from the spray flow.



**Fig. 7** Chamber support structures and supply lines.

A much more substantial mounting scheme has been designed for the cylindrical jet array nozzles due to the large steady reaction forces they will experience. To minimize deflection, each of these nozzles is mounted on two “I-Beams” attached to the vacuum vessel and protruding through the FSW. Their geometry provides space for the molten salt pipes feeding this flow which protrude through the vacuum barrier and the nozzles can be disconnected from their supports for servicing.

Various scaled experiments with water (see Figure 6(b)) have studied the exact components that would make up the individual nozzles generating the smooth jets in the cylindrical jet array. Some critical components would include flow conditioning honeycomb and wire mesh [8] along with adjustable inlet plenums to fine tune jet trajectories for proper ion beam standoff.

The molten salt protecting the upper chamber structures is contained within a shield tray supported and supplied from a rafter system above (reference Figure 7). These rafters support this component as well as the flow guiding chamber and pocket nozzles whenever the chamber top is removed for maintenance. When in place, though, the top provides the primary structural reinforcement.

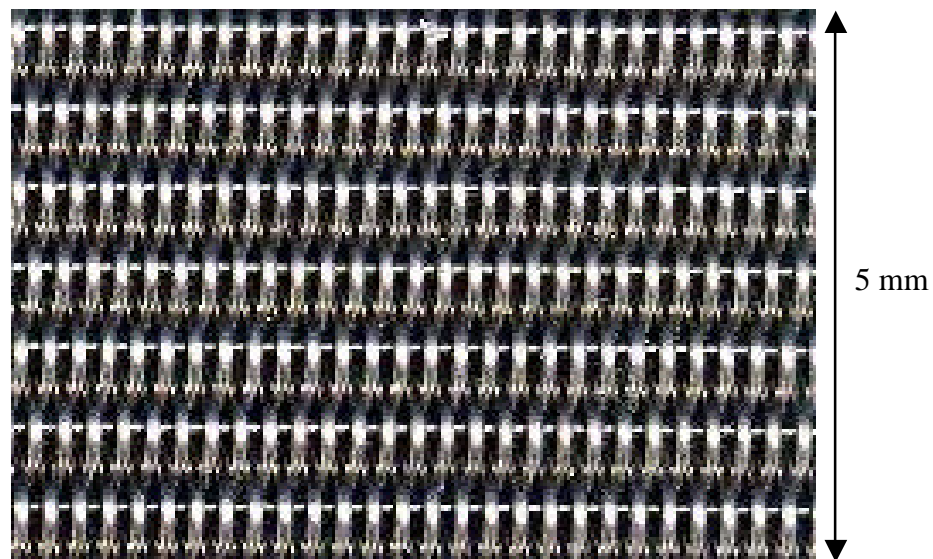
## **FIRST STRUCTURAL WALL**

In the HYLIFE-II design, 304SS was specified as the fusion chamber structural material. Among the reasons motivating this choice were availability, corrosion resistance, and low activation. An estimated neutron radiation damage limit of 100 displacements per atom (dpa) was used in calculating a liquid blanket shielding thickness of 0.56 m so that a 30 year plant life could be achieved with no replacement of the FSW. A recent study of IFE structural materials conducted by the ARIES team found that 304SS would experience significant volumetric swelling and helium embrittlement issues at as low as 25 dpa [9]. Modifications of to the HYLIFE-II FSW design for RPD-2002 were required to accommodate material damage uncertainty at lower neutron fluences.

Several possible approaches were considered. Among these were changing the FSW material, thickening the pocket flow, and modifying the geometry of the HYLIFE-II design. All routes posed tradeoffs. Selecting a new material involved trading higher neutron damage limits for molten salt compatibility. A thicker pocket flow requires more power, reducing the plant efficiency. In the end, a geometric approach was taken and the rigid tubes of the HYLIFE-II FSW were replaced with flexible 304SS wire-mesh.

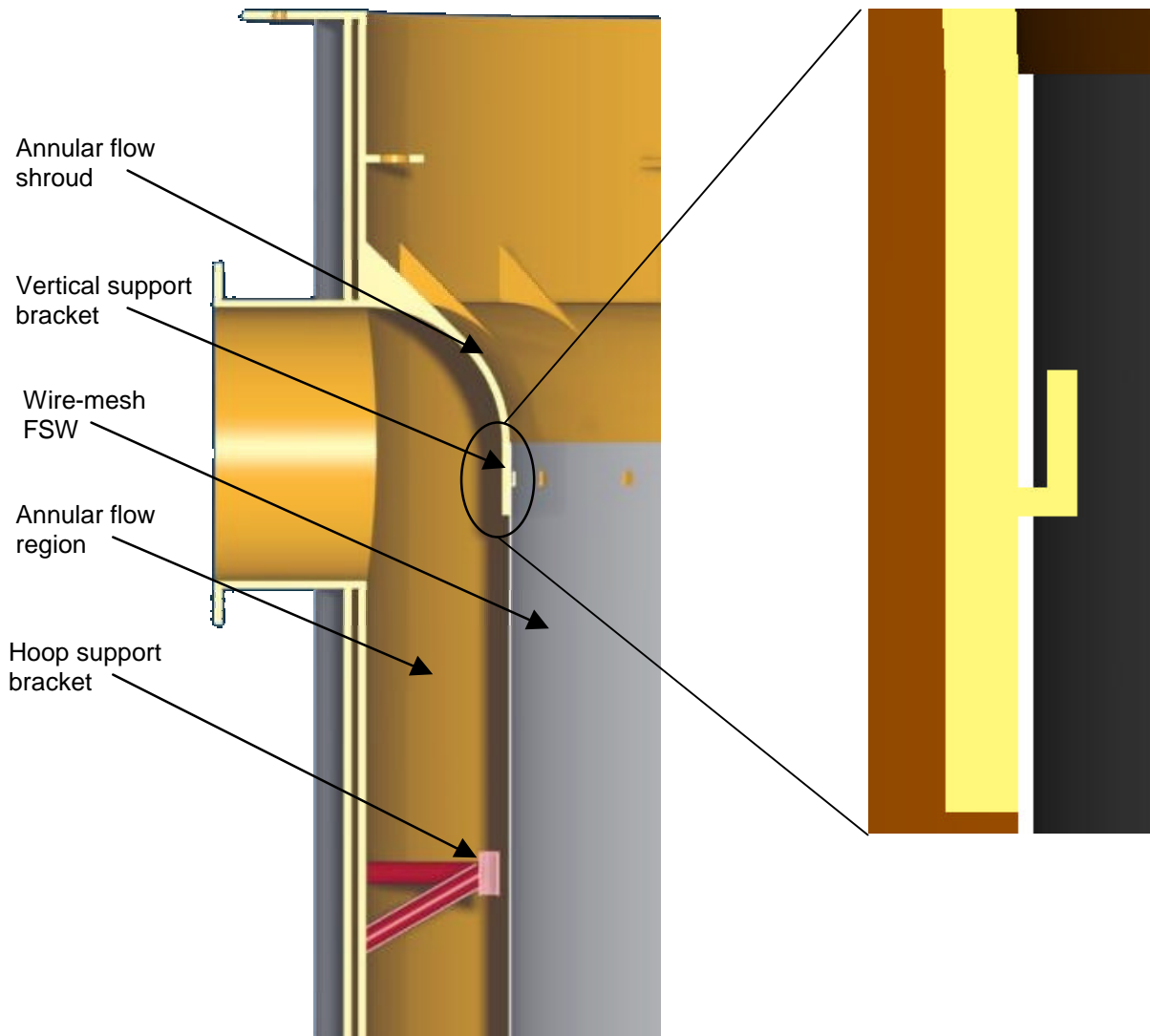
Making the FSW of the fusion chamber from wire-mesh mitigates the swelling and embrittlement issues geometrically. Because the elements of wire-mesh (the wires) have small characteristic dimensions and the overall structure can exhibit large void fractions, significant volumetric swelling can be withstood without inducing large deformation related stresses threatening the integrity of the FSW. Also, whereas cracks in solid structures can propagate long distances and cause catastrophic failures, a crack in a wire-mesh structure can extend over only a single wire. There will be an associated rise in nominal stresses in the undamaged mesh when a wire breaks, but this is a less

severe situation than a large crack. Chances of helium embrittlement resulting in large-scale brittle fracture are thus mitigated. Because wire-mesh can be made with a variety of specifications for wire diameter and mesh density, thermal stress issues from neutron heating can be addressed and designed for. There is similar design room for cooling a wire-mesh FSW. The amount of “weeping,” and hence heat transfer, from the annular flow behind the FSW can be tailored. Figure 8 is an example of wire-mesh commercially available. If FSW replacement is required, it is considerably easier to remove a flexible segmented wire-mesh structure than a solid wall.



**Fig. 8** Wire-mesh.

Figure 9 shows schematically how a wire-mesh FSW might be mounted to make periodic removal and replacement possible. The mesh is supported vertically against gravity by mounting it from brackets placed around the reinforced shroud at the top of the annular flow region. To provide hoop strength, arrays of mounting brackets attached to the vacuum wall support the wire-mesh against the inward pressure of the annular molten salt flow. Having no permanent connections allows the FSW to be lifted off the mounting brackets and pulled out of the chamber by crane.



**Fig. 9** FSW support features.

## **CHAMBER DISASSEMBLY**

The mechanical design of the RPD-2002 fusion chamber addresses uncertainty in what lifetimes can be expected from internal chamber components by making it possible to periodically remove and replace them as needed. These operations can be carried out remotely with only overhead cranes and simple robotic manipulators. An animation illustrating this process has been created and can be obtained in electronic form from the author.

## SUMMARY

A mechanical design for the RPD-2002 fusion chamber has been introduced. It is based largely on thick liquid protected HYLIFE-II chamber with modifications making it compatible with current designs for other plant systems. The pocket configuration has been updated to support two sided target illumination, the HYLIFE-II FSW concept has been replaced with a flexible wire-mesh FSW to tolerate large neutron induced swelling, and the arrangement of internal chamber systems has been updated to allow for periodic removal and maintenance.

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